

Which bulges are favoured by barred S0 galaxies?

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ABSTRACT

S0 galaxies are known to host classical bulges with a broad range of size and mass, while some such S0s are barred and some not. The origin of the bars has remained as a long-standing problem – what made bar formation possible in certain S0s?

By analysing a large sample of S0s with classical bulges observed by the Spitzer space telescope, we find that most of our barred S0s host comparatively low-mass classical bulges, typically with bulge-to-total ratio (B/T) less than 0.5; whereas S0s with more massive classical bulges than these do not host any bar. Furthermore, we find that amongst the barred S0s, there is a trend for the longer and massive bars to be associated with comparatively bigger and massive classical bulges – possibly suggesting bar growth being facilitated by these classical bulges. In addition, we find that the bulge effective radius is always less than the bar effective radius – indicating an interesting synergy between the host classical bulge and bars being maintained while bar growth occurred in these S0s.

Key words:

galaxies: elliptical and lenticular - fundamental parameters galaxies: photometry - structure - bulges galaxies: formation - evolution

1 INTRODUCTION

Lenticular (S0) galaxies in the local universe are primarily characterised by the presence of a bulge and disc with no apparent spiral arms (Barway et al. 2007; van den Bergh 2009) - but a number of observations have shown that like their progenitor spirals, S0 galaxies, especially the low luminous ones, are both barred and unbarred (Barway, Wadadekar & Kembhavi 2011; van den Bergh 2012). What has made bar formation possible in some S0 galaxies has remained a long standing puzzle.

Significant progress has been made over the last decade or so in terms of our understanding of the redshift evolution of bars in disc galaxies. A number of these studies suggest that the bar fraction in spiral galaxies is strongly dependent on their mass (Nair & Abraham 2010; Cameron et al. 2010). It has been shown that the bar fraction in low-mass spirals remains nearly constant out to $z \sim 1$, corresponding to a look-back time of 7.8 billion years (Elmegreen, Elmegreen & Hirst 2004; Jogee et al. 2004; Barazza, Jogee, & Mari-

nova 2008; Nair & Abraham 2010; Cameron et al. 2010). More recently, Simmons et al. (2014) using the HST CANDELS survey extended such a study to $z \sim 2$ and found no significant change in the bar fraction. These findings imply that bars are robust stellar structures; once formed, it is hard to destroy them. Based on the modelling of stellar kinematics, it is believed that the barred spirals were the progenitors of the present-day barred lenticulars which got rid of their spirals (Cortesi et al. 2011, 2013) - it becomes clearer that bars in the present-day S0s have formed long back, most likely during the cosmic assembly of disc galaxies. During those early phase of evolution, a disc would have assembled and grown around a classical bulge either merger-built (Kauffmann, White & Guiderdoni 1993; Baugh, Cole, & Frenk 1996; Hopkins et al. 2009) or formed as a result of other processes likely to be active in the high-redshift universe e.g., clump coalescence, violent disc instability etc. (Elmegreen, Bournaud & Elmegreen 2008; Ceverino et al. 2015). Then one would expect the classical bulge to intervene the bar formation process that occurred in the host stellar disc of the present-day S0s.

Indeed, Barazza et al. (2008) showed that bar fraction rises sharply from $\sim 40\%$ to 70% as one moves from early-type to late-type galaxies which are disc dominated rather

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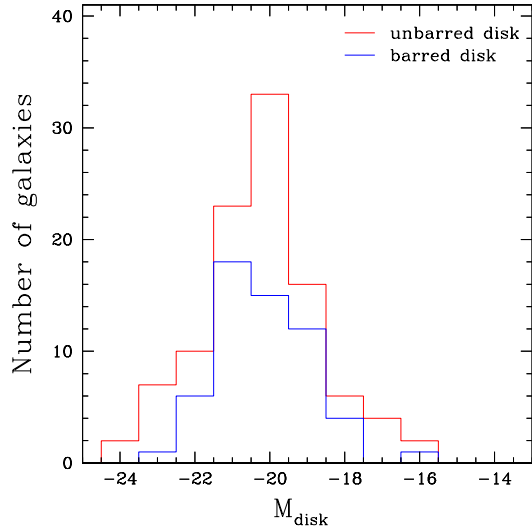


Figure 1. Distribution of absolute magnitudes (in $3.6 \mu m$) of the host stellar discs in barred and unbarred S0 galaxies. Both barred and unbarred discs seem to have similar range of disc luminosities.

than ones with prominent bulges. A massive classical bulge can produce a strong inner Lindblad resonance (ILR) barrier to prevent the feedback loop required for the swing amplification mechanism to work effectively in the disc leading to the formation of a bar in the first place (Dubinski, Berentzen & Shlosman 2009). So it is desirable for a stellar disc to not have a strong ILR in the early phase of galaxy assembly. A massive classical bulge can also produce enough central concentration to create destructive effect on the orbital backbones of a bar (Pfenniger & Norman 1990; Hasan, Pfenniger & Norman 1993). Overall, it turns out that a massive classical bulge and a bar might not coexist in a spiral galaxy. But it remains unclear how to reconcile this with the observed properties of bars and classical bulges in S0 galaxies. The primary aim of the current work is to understand what physical parameters of a classical bulge are a pre-requisite for a bar to form and grow stronger in a S0 galaxy.

The paper is organised as follows. Section 2 describes the sample data and its analysis. The role of S0 discs and classical bulges in the context of bar formation are considered in section 3 and section 4. Section 5 is devoted to discussion and conclusions. Throughout this paper, we use the standard concordance cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $h_{100} = 0.7$.

2 SAMPLE

The sample used in this Letter is described in detail in Vaghmare et al. (2015). The parent sample comprises 1031 galaxies, visually classified as S0 in the RC3 catalogue (de Vaucouleurs et al. 1991) and having an integrated B-band magnitude brighter than 14.0. This parent sample is cross-matched with the Spitzer Heritage Archive (SHA) and 247 galaxies are found with $3.6 \mu m$ imaging data. The Level 1 or Basic Calibrated Data were obtained from SHA and a co-added mosaic was constructed using MOPEX (MOsaicking and Point EXtraction tool). Structural parameters for

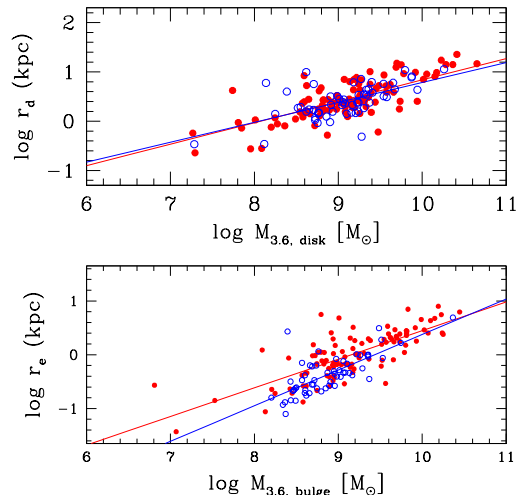


Figure 2. Top panel: Size -mass relation for the disc hosting classical bulges in the $3.6 \mu m$. Filled red circles are unbarred S0s and open blue circles are barred S0s. Solid lines are best fit line to the data. Bottom panel: the same for the classical bulges only (unbarred and barred).

the bulge, disc and bar components of these galaxies were derived using GALFIT (Peng et al. 2002) on the mosaics. In the first run, we fitted all galaxies with a bulge and a disk using a Sérsic (Sersic 1968) and an exponential profile simultaneously. In cases, where the residual image obtained by subtracting the Point Spread Function convolved best-fit model from the observed image revealed a bar, a second run of fitting was performed by adding another Sérsic component to describe the bar. Inclusion of an additional bar component do not show any difference for Sérsic index n values for both barred and unbarred classical bulges, respectively. We also found some galaxies that were visually classified as S0s, had spiral like features in GALFIT residual images. We have removed them, in addition to those with bad fits, poor quality images from our subsequent analysis. Our final sample comprises of 185 S0 galaxies with median redshift of 0.005.

In order to classify the bulges, the authors, in Vaghmare, Barway & Kembhavi (2013), used a combination of two well established criteria in the literature. All bulges deviating more than $3 - \sigma$ below the best-fit line to the Kormendy relation to ellipticals (Gadotti 2009) and having a Sérsic index $n < 2$ (Fisher & Drory 2008) were classified as pseudo bulges, while the rest were classified as classical bulges. The sample comprises 25 pseudo bulge hosts with the remaining the 160 being classical bulge hosts. 65 of 160 classical bulge hosts are barred. To determine the masses of the bulges and discs in our galaxies, we used a prescription by Cook et al. (2014) to obtain the M/L ratios at $3.6 \mu m$. In this paper, we consider the relationship between classical bulges and bars. Our current sample does not have a large enough number of pseudo bulges to investigate their relationship to bars in S0 galaxies (see Vaghmare et al. (2015)). Hereafter, we refer a classical bulge as a bulge unless stated otherwise.

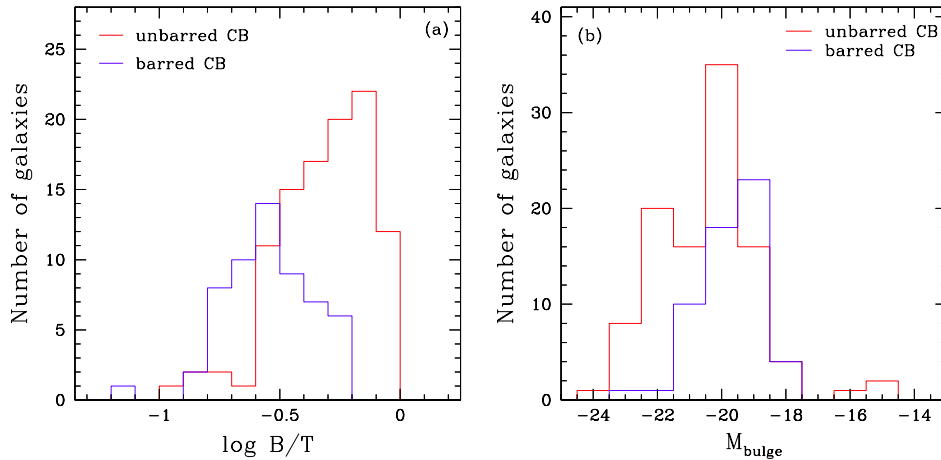


Figure 3. **a.** Bulge-to-total ratios (B/T) distribution for classical bulges. Bars are associated with comparatively low B/T s. **b.** Absolute magnitude distribution for the classical bulges.

3 ROLE OF S0 DISCS ON BAR FORMATION

It is well known that massive cool self-gravitating discs are, in general, prone to bar instability - leading to the formation of strong bars as shown by a number of simulations (Hohl 1971; Debattista & Sellwood 1998; Athanassoula 2003; Saha, Martinez-Valpuesta & Gerhard 2012). Whereas lower mass, comparatively hotter galaxies tend to avoid forming strong bars (Saha, Tseng & Taam 2010; Sheth et al. 2012; Saha 2014). When it comes to S0 galaxies in the local universe, bars are preferentially observed in low-luminous S0s (Barway et al. 2011) - which is a puzzling issue. Here we study the global properties of stellar discs of S0s to disentangle their role played in the formation of a bar.

A three-component (bulge-bar-disc) decomposition of each S0 galaxy provides us the structural information about stellar discs. All stellar discs are well modelled by an exponentially falling surface brightness distribution with scale length r_d and central surface brightness I_0 . Using these and the distance information, we compute the absolute magnitude M_{disc} of the disc in the $3.6 \mu m$. In Fig. 1, we show the distribution of M_{disc} for 160 galaxies with classical bulges. *This sample has been sub-divided into two - a subsample of barred galaxies and that of unbarred.* What we notice is that, overall, the histograms of disc luminosity appear remarkably similar in either case. In other words, we do not find any particular luminosity range being preferred by an S0 disc to host a bar. This is also being reflected in the top panel of Fig. 2, showing the relation between the disc scale length and disc stellar mass - the so called *size-mass relation* (Gadotti 2009). *We find that both barred and unbarred stellar discs follow nearly the same size-mass relation.* In other words, where bar formation is concerned, there is no circumstantial preference for either low-mass (hence low luminous) or high-mass discs in the current S0 sample. However, a conclusive remark on this aspect requires one to probe an even larger sample of stellar discs without an environmental or morphological bias. In the following, we investigate whether the incidence of a bar in our sample S0s depends on the presence of a classical bulge.

4 CLASSICAL BULGE AND BAR CONNECTION

Classical bulges and bars coexist in spiral galaxies across the Hubble sequence from late-type to early-type and S0s. Yet, it remains to be established whether classical bulges play any role in the bar formation. Part of the difficulty lies in disentangling whether bars formed after the classical bulges, or both formed nearly simultaneously, or bars existed before the classical bulges formed. We consider the first as a viable scenario - as might have been the case if major mergers formed a classical bulge and the disc assembled around it gradually and became self-gravitating leading to the formation of bars. All the S0s in the current sample that host classical bulges, the bar being the only morphological entity used to classify them into two categories - barred and unbarred. In other words, the S0 discs plus classical bulge acts as a base structure. In some cases, this structure allows for a bar to grow and in some cases, it does not. On what aspects of this base structure does the bar formation depend on, remains one of the outstanding issues in astronomy. Below, we attempt to unravel a link between classical bulge properties and growth of bar in the stellar disc.

First, we study the bulge-to-total ratios B/T in our current sample (see Fig. 3(a)). We find that the distribution of B/T is clearly separated for barred and unbarred S0s, with mean $B/T \sim 0.35$ for barred S0s and ~ 0.7 for unbarred ones. Although $\sim 30\%$ of the total luminosity in the bulge is substantial compared to late-type galaxies, where S0s are concerned, this is considered to be small. So we calculated the absolute bulge luminosity and found that the bulges in barred S0s are actually of lower luminosity compared to those in unbarred ones by ~ 1 magnitude (Fig. 3(b)). Bottom panel of fig. 2 shows the size-mass relation for all the classical bulges. It is obvious from the figure that both the effective radii r_e and stellar mass of classical bulges are smaller in S0s with bars than those without any bar. A large fraction of the classical bulges in barred S0s have masses falling in the range $\sim 10^8 - 10^9 M_\odot$ while their disc mass scatter around few $\times 10^9 M_\odot$. In other words, *we do see a preference of smaller low-mass classical bulges to be associated with barred S0s over unbarred ones.* This, in

turn, would imply that perhaps bar formation was hindered in galaxies with massive bulges in the central region. Since a massive bulge would produce a strong inner Lindblad resonance (ILR) which might cut the feedback loop necessary for the swing-amplification (Toomre 1981) to work efficiently and thereby slowed down or even stopped growing a bar in the first place.

4.1 Correlation between bar-bulge parameters

The idea here is to find out whether there is a deeper connection between a bar and a classical bulge in a barred S0 galaxy. Fig. 4 (a) shows that there is a trend for longer bars to be associated with bigger bulges. It is interesting to note that effective radii of the classical bulges are less than or equal to the disc scale length whereas bars come with a wider range of sizes. In addition to the bar-bulge size correlation, Fig. 4 (b) reveals a clear trend of massive bars being associated with massive classical bulges amongst the barred S0s. Taken together, it implies that longer and massive bars are developed in those S0s which host bigger and comparatively massive classical bulges. In other words, *massive, bigger classical bulges seem to facilitate bars to grow longer and be more massive*. Note that this holds true only for the barred S0s having $B/T < 0.5$ as found in the current sample. To strengthen this further, *we constructed a subset of barred S0s whose stellar disc masses were nearly equal*. Fig. 4 (c) shows a rather strong correlation between the bulge mass and bar mass for those S0s. What might have happened is that these comparatively low B/T classical bulges allowed the bar formation in the first place because of lowered ILR strength and subsequently facilitated the bar growth via resonant gravitational interaction (Saha et al. 2012; Saha & Gerhard 2013; Saha, Gerhard & Martinez-Valpuesta 2016). Needless to say the surrounding dark matter halo would also play a similar role alongside but we do not have any information about the halo at this point, except input from simulations, see section 5 below.

5 DISCUSSION

The role of a classical bulge in the growth and evolution of a bar has not been fully investigated. It is known that a massive centrally concentrated object (e.g., a supermassive black hole) can considerably weaken a bar by scattering stars off the x_1 -family of orbits which constitute the backbone of the bar (Hasan et al. 1993; Sellwood & Moore 1999; Athanassoula, Lambert & Dehnen 2005; Hozumi & Hernquist 2005; Hozumi 2012). Some of the classical bulges in the current sample have the right mass for such action, but are not as centrally concentrated as might be required to have a supermassive black hole like effect. But such massive classical bulges could, in principle, delay or even stop a bar from forming in the first place by producing an ILR near the centre of the galaxy, which would cut the feedback loop required for the swing amplification (Toomre 1981). In fact, as mentioned in section 4, we do find S0 galaxies with massive classical bulges as unbarred. This agrees with the reported Barazza et al. (2008) bar fraction reduction in disc galaxies with rising bulge-to-disc mass ratio.

It remains unclear why some spiral galaxies are barred

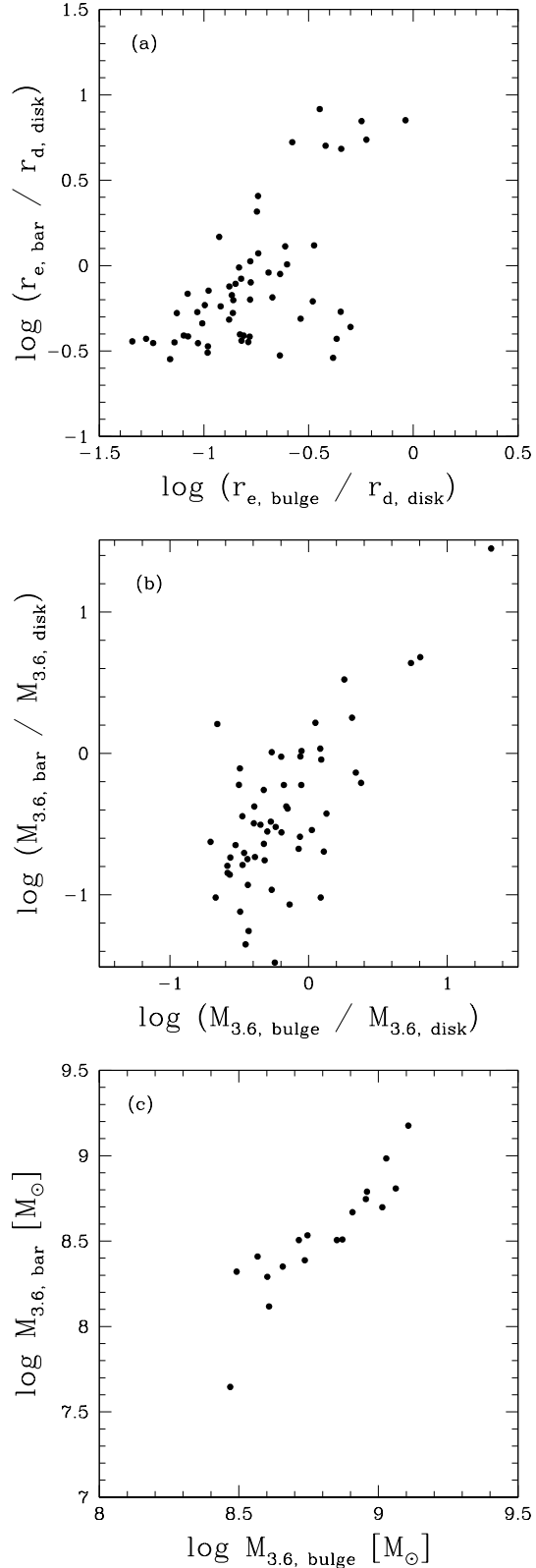


Figure 4. Correlation between the bar and classical bulge parameters for barred S0 galaxies. **a.** Correlation between bar effective radii $r_{e, \text{Bar}}$ and bulge effective radii $r_{e, \text{bulge}}$, normalised by the disc scale lengths r_d . **b.** Normalised bar mass plotted against normalised bulge mass. **c.** Bulge mass versus bar mass in units of M_\odot for those S0s with nearly same disc mass $\sim 2 \times 10^9 M_\odot$.

and some are not. Not only spiral galaxies, but as we see here, S0s also face the same unresolved issue. In order to make progress, one has to disentangle the effect of various parameters of the disc, classical bulge and dark matter halo which determine the bar growth in a galaxy. N-body simulations have shown that a bar forms and grows rapidly in a cool, rotating self-gravitating disc (Hohl 1971; Sellwood & Wilkinson 1993; Athanassoula 2002; Dubinski et al. 2009; Saha et al. 2012, and references therein). Furthermore, the bar continues to grow in size and mass by transferring angular momentum from the inner disc to the surrounding dark matter halo via resonant gravitational interaction (Debatista & Sellwood 1998; Athanassoula 2002; Holley-Bockelmann, Weinberg & Katz 2005; Weinberg & Katz 2007; Ceverino & Klypin 2007; Saha & Naab 2013). But if the initial disc was hotter and dark matter dominated, a bar would grow rather slowly over several billion years and might remain weak and be too faint to be detected (Saha et al. 2010; Sheth et al. 2012; Saha 2014). These two inputs lead us to suggest that the bars in S0s are unlikely to have formed in their later phase of evolution. In other words, we think that bars in S0s formed during the early phase of disc assembly around a classical bulge with a comparatively lower B/T . Bars in S0 galaxies are preferentially formed in the presence of classical bulges with lower $B/T < 0.5$. These classical bulges have their stellar mass in the range $\sim 10^8 - 10^9 M_\odot$. Massive classical bulges with $B/T > 0.5$ are not found in any barred S0s in our sample. Amongst barred S0s with similar disc mass, there exist a strong correlation between the bar and classical bulge properties. The host stellar discs are unlikely to have played a major role in the formation of bars in these S0s.

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